AFCRL-71-0291

AD 727775

SEISMIC TRAVEL TIME STUDY

by

Anton L. Hales

The University of Texas at Dallas
P. O. Box 30365
Dallas, Texas 75230

Contract No. F19628-70-C-0176
Project No. 5130

FINAL REPORT

15 January 1970 - 14 April 1971

March 1971

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency or the U.S. Government.

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24

Program Code No..9F10

Effective Date of Contract............................6 January 1971

Contract Expiration Date..............................14 January 1972

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214-231-1471

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ABSTRACT

This report consists of an introduction in which is given a list of published papers on the travel times of body waves together with brief comments on the results.

The main body of the report describes a new determination of the velocity distribution in the outer core.

Earlier studies of the velocity distribution in the outer core have been based on the travel times of SKS. However, SKS arrivals can only be observed satisfactorily for arc distances at the surface greater than 83°. This lower limit of observation of SKS corresponds to an arc distance of 40.2° within the core. Thus the velocities in the outermost 250 km of the core are based upon an extrapolation. We have used observations of the difference in time of arrival of SKKS and SKS to obtain core travel times extending the range of observation down to a Δ within the core of 14.5°. The velocities thus found are significantly lower than those of Jeffreys-Bullen and Randall near the core mantle boundary.

Scientists contributing to the research under this contract: A.L. Hales and J.L. Roberts.

INTRODUCTION

The papers dealing with body wave travel time studies published during the currency of this series of contracts are:

Cleary, J. R. and A. L. Hales, "An analysis of the Travel Times of P Waves to North American Stations, in the Distance Range 32° to 100°," Bull. Seism. Soc. Am., 56 (2), pp. 467-489, 1966

Cleary, J. R. and A. L. Hales, "Azimuthal Variation of U.S. Station Residuals," Letter to the Editor, Nature, 210 (5036), pp. 619-620, 1966

Doyle, H. A. and A. L. Hales, "An Analysis of the Travel Times of S Waves to North American Stations, in the Distance Range 28° to 82°," Bull. Seism. Soc. Am., 57, 761-771, 1967

Hales, A. L. and H. A. Doyle, " P and S Travel Time Anomalies and Their Interpretation," Geophys. J.R.A.S., 13, pp. 403-415, 1967

Hales, A. L. and J. R. Cleary and J. L. Roberts, "Velocity Distribution in the Lower Mantle," Bull. Seism. Soc. Am., 58, no. 6, pp. 1975-1989, 1968

Hales, A. L. and J. L. Roberts, "The Travel Times of S and SKS," Bull. Seis. Soc. Am., 60, 6, pp. 461-489, 1970

Hales, A. L. and J. L. Roberts, "Shear Velocities in the Lower Mantle and the Radius of the Core," Bull Seis. Soc. Am., 60, 5, pp. 1427-1436, 1970

In addition, two review papers were prepared:

Hales, A. L., J. R. Cleary, H. A. Doyle, R. Green and J. Roberts, "P-Wave Station Anomalies and the Structure of the Upper Mantle," J. Geophys. Res., 73, pp. 3885-3896, 1968

Hales, A. L., and E. T. Herrin, "Travel Times of Seismic Waves," submitted to U.S. Geological Survey, 1970

During the past year a paper dealing with the travel times of SKS and SKKS and the velocities in the outer core has been completed and submitted for publication (Hales, A.L. and J.L. Roberts, "Velocities in the Outer Core," submitted to Bull. Seis. Soc. Amer., 1971).

In a study (not funded under the contract but clearly related to the travel time study) Cleary and Hales (Cleary, J.R. and A.L. Hales, "PKIKP Residuals at Stations in North America and Europe," Earth and Planetary Science Letters, 8, 4, pp. 279-282, 1970) showed that there is a strong correlation between station anomalies determined from PKIKP and those determined from P. They showed furthermore, that the Lilwall and Douglas suggestion with regard to bias in the Cleary and Hales and Herrin and Taggart determination of station anomalies, was not correct.

A paper (Cleary, J.R. and A.L. Hales, "PKIKP Times and Station Anomalies," submitted to Jour. Geophys. Res., 1971) dealing with PKIKP travel times has been submitted.

As was expected when this series of travel time studies began, the deviations from the standard tables have turned out to be relatively small. However, the increased accuracy of modern stations and their great density has permitted the separation of the residuals into components, one of which is related to upper mantle structure near the stations. It has been shown furthermore that the ratio of this component for S and P is larger than would have been expected except on the hypothesis that partial melting occurs in the upper mantle and in tectonically active areas.

THE VELOCITIES IN THE OUTER CORE

Introduction

Travel times for SKS from 84° to 126° were reported in a recent paper (Hales and Roberts, 1970a). It was noted that it was not possible to identify SKS satisfactorily for distances less than 83° because SKS is obscured by the earlier arriving S phase. This creates a difficulty in the determination of the velocities in the outer core since the arc distance Δ_K traversed within the core is about 50° for a Δ_{SKS} of 90°.

Observations of SKKS

A special study was made of the difference in arrival time of SKKS and SKS in order to obtain times for values of Δ_K less than 50°. These differences are presented as functions of Δ in figure 1. The observations at distances from 110° to 130° are of high quality as can be seen from the records reproduced in figure 2. This is especially true of the records at near radial azimuths. At shorter distances, especially close to 84°, SKKS follows very closely behind SKS and the separation is difficult. The readings at the shorter distances in figure 1 were based on records in which the two phases were out of phase and as a result the time of arrival of the second phase could be identified with moderate certainty.

After correcting the readings for ellipticity and depth of focus, the observed differences (t_{SKKS} - t_{SKS}) were added to the corresponding t_{SKS} polynomial from Hales and Roberts (1970a)

$$t_{SKS} = 1493.96 + 4.61\ (\Delta-105.0)-0.0440(\Delta-105.0)^2. \qquad (1)$$

The polynomial

$$t_{SKKS} = 1539.18 + 7.02\ (\Delta-105.0)-0.0161(\Delta-105.0)^2 \qquad (2)$$

was fitted to these values with an RMS deviation of

2.76 sec. From (1) and (2)

$$t_{SKKS} - t_{SKS} = 45.22 + 2.41\ (\Delta-105.0) + 0.0279\ (\Delta-105.0)^2. \quad (3)$$

This polynomial is plotted on figure 1.

Core Travel Times

The values t_K and Δ_K for the core phases were obtained by matching the p's ($dt/d\Delta$), SKS, and SKKS with the corresponding p's from the ScS travel times calculated for the SLUTD 1 velocity distribution of Hales and Roberts (1970b) and a core radius of 3477 kms (Taggart and Engdahl, 1968). (This is equivalent to using the polynomial representation of S travel times given by Hales and Roberts, 1970a.) The values of p, t_K and Δ_K found in this way are given in figure 3. In this figure we indicate the SKS and SKKS arc distances which correspond to the p, t_K and Δ_K shown.

The values of t_K and Δ_K found above are each associated with a particular value of p. For SKS the extreme values are

TABLE 1

Δ_{SKS}	t_{SKS}	p	Δ_K	t_K
85°	1384.12	365.08	40.21°	287.83
126°	1571.40	158.37	109.87°	611.03

and for SKKS

TABLE 2

Δ_{SKKS}	t_{SKKS}	p	Δ_K	t_K
90°	1430.30	429.71	14.47°	110.18
126°	1679.49	363.48	40.76°	292.60

It is clear from figure 3 that the p's found from the stripped SKKS times and those from the stripped SKS times match extremely well at 40° to 41°. The times t_K derived from SKKS and SKS do not match quite as well, the discrepancy being of the order of 1.4 secs. This is within the error of the SKS and SKKS observations.

In order to determine t_K and p_K for Δ_K less than 14° it is necessary to make some assumption. A velocity at the core-mantle boundary can be determined by applying to SKKS a method devised by Randall (1970) for SKS. Assuming a velocity distribution $v = v_0 \ (r/r_0)^{\alpha}$ where the zero suffixes denote values at the core-mantle boundary it follows that

$$p = (dt_K/d\Delta_K) = (\pi r_o/180v_o) \quad \cos\,[\Delta_K(1-\alpha)/2]$$

$$t_K = (2r_o/(1-\alpha)V_o) \quad \sin\,[\Delta_K(1-\alpha)/2].$$

Using the SKKS information for t_K, p_K and Δ_K corresponding to Δ_{SKKS} = 85, 90, 95 and 100° we find v_o = 7.909, 7.907, 7.893 and 7.893 km/sec respectively. These velocities are much lower than the Jeffreys velocity of 8.10 km/sec at the core-mantle boundary. Randall (1970) using Hales and Roberts (1970a) times for SKS finds v_o = 8.256 km/sec. Values of $p_K = \frac{dt_K}{d\Delta_K}$ corresponding to the Jeffreys and Randall velocity values are marked on figure 3. Clearly, if the SKKS times are valid these values of $(dt_K/d\Delta_K)$ are too low, i.e. the core velocities at the core-mantle boundary too high.

It will be noted from figure 3 that $(dt_K/d\Delta_K)$ decreases linearly with Δ_K over the range for which stripped values of p_K, t_K and Δ_K can be found from both SKKS and SKS. It was found earlier that $(\frac{dt}{d\Delta})_P$ and $(\frac{dt}{d\Delta})_S$ decrease linearly as functions of Δ over the range from 30° to 85° (Hales, Cleary and Roberts, 1968; Hales and Roberts, 1970a; and Hales and Herrin, 1971). This coincidence suggests that the close approximation to a linear decrease of $dt/d\Delta$ with Δ arises from some property related to the equation of state for a homogeneous material under increasing pressure and in a nearly adiabatic temperature gradient.

Velocities determined by applying the Herglotz-Wiechert procedure to the stripped p_K, Δ_K values are given in Table 3 and plotted in figure 4. Also shown in figure 4 are the Jeffreys (Bullen, 1963) and Randall velocities. Times determined by integration of the p_K values as a function of Δ,

or directly from the velocity model, are plotted in figure 3. They fit the observed times well for SKKS and are off by 1.4 secs for SKS. The velocity in the core is determined down to a radius of 1624 km.

As a further check on the core velocities we compare in Table 4 observed and calculated values for $t_{SKKKS} - t_{SKKS}$ for the three reasonably good records reproduced in figure 5.

TABLE 4

DISTANCE (DEGREES)	$t_{SKKKS}-t_{SKKS}$ OBSERVED (SEC)	$t_{SKKKS}-t_{SKKS}$ (this paper) (SEC)	$t_{SKKKS}-t_{SKKS}$ Randall (SEC)	$t_{SKKKS}-t_{SKKS}$ J-B TABLES (SEC)
151.55	41.99	41.59	33.29	36.79
156.02	48.49	46.47	38.42	42.61
161.17	56.23	52.42	44.77	48.87

Travel times for the ABC branch of PKP were calculated using the P velocity distribution of Hales and Herrin (1971) and the core velocities of Table 3. The point A for the model came at $\Delta = 178.8°$ and the cusp B at 142.3°. For PKKP, PKKKP, PKKKKP and PKKKKKP the points A occur at arc distances of 101.5°, 21.8°, 57.8°, 137.5° respectively and the points B at 124.3°, 38.9°, 44.1°, 126.0° respectively.

We summarize in figure 6 some parameters of the new outer core velocity distribution.

Discussion

The velocities found for the outermost 300 km of the outer core are appreciably lower than those found earlier. However, so far as we know all earlier estimates of the velocities in this region were based upon extrapolations of times found from SKS observations. The observations of the differences between the arrival time of SKKKS and SKKS lend support to the new velocity distribution for the calculated differences based on the earlier velocity distribution are significantly smaller than the observed differences. The new velocity distribution satisfies other constraints such as

the existence of the cusp B close to 143°, the arrivals being two or three seconds earlier than DEF branch for distances of a few degrees beyond the cusp. The cut off points A agree reasonably well with the observations of Engdahl (1968).

Acknowledgements

The research on seismic body wave travel times of which this paper is part has been sponsored by the Air Force Cambridge Research Laboratories, Air Force Systems Command, under Contract AF-196282936 and its continuations, F19628-67-C-0419 and F19628-70-C-0176, but the report does not necessarily reflect endorsement by the sponsor. We have pleasure in acknowledging the last named contract which provided support for the SKS, SKKS study.

Our thanks are due to E.R. Engdahl of National Oceanic and Atmospheric Administration who kindly provided us with a copy of his Ph.D. thesis.

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Randall, M.J., 1971. SKS and seismic velocities in the outer core, in press.

Taggart, J.N. and Engdahl, E.R., 1968. Estimation of PcP travel times and the depth to the core, Bull. Seis. Soc. Am., 58, 1293-1303.

TABLE 3

RADIUS (KMS)	VELOCITY (KMS/SEC)	RADIUS (KMS)	VELOCITY (KMS/SEC)	RADIUS (KMS)	VELOCITY (KMS/SEC)
3477.0	7.907	2860.0	8.916	2240.0	9.589
3460.0	7.936	2840.0	8.940	2220.0	9.610
3440.0	7.970	2820.0	8.964	2200.0	9.631
3420.0	8.005	2800.0	8.987	2180.0	9.651
3400.0	8.048	2780.0	9.010	2160.0	9.672
3380.0	8.092	2760.0	9.033	2140.0	9.693
3360.0	8.135	2740.0	9.056	2120.0	9.714
3340.0	8.178	2720.0	9.078	2100.0	9.734
3320.0	8.219	2700.0	9.101	2080.0	9.755
3300.0	8.259	2680.0	9.123	2060.0	9.776
3280.0	8.298	2660.0	9.145	2040.0	9.797
3260.0	8.335	2640.0	9.167	2020.0	9.818
3240.0	8.372	2620.0	9.189	2000.0	9.839
3220.0	8.407	2600.0	9.211	1980.0	9.860
3200.0	8.442	2580.0	9.232	1960.0	9.881
3180.0	8.475	2560.0	9.254	1940.0	9.903
3160.0	8.508	2540.0	9.275	1920.0	9.924
3140.0	8.540	2520.0	9.296	1900.0	9.945
3120.0	8.572	2500.0	9.318	1880.0	9.967
3100.0	8.602	2480.0	9.339	1860.0	9.988
3080.0	8.631	2460.0	9.360	1840.0	10.010
3060.0	8.660	2440.0	9.381	1820.0	10.032
3040.0	8.687	2420.0	9.402	1800.0	10.054
3020.0	8.714	2400.0	9.423	1780.0	10.076
3000.0	8.741	2380.0	9.444	1760.0	10.098
2980.0	8.767	2360.0	9.465	1740.0	10.120
2960.0	8.793	2340.0	9.485	1720.0	10.143
2940.0	8.818	2320.0	9.506	1700.0	10.165
2920.0	8.843	2300.0	9.527	1680.0	10.188
2900.0	8.868	2280.0	9.548	1660.0	10.211
2880.0	8.892	2260.0	9.568	1640.0	10.234
				1620.0	10.257

FIGURE CAPTIONS

Figure 1. Observations of $t_{SKKS}-t_{SKS}$ from 35 events (141 observations).

Figure 2a. Examples of records used to determine $t_{SKKS}-t_{SKS}$.

(A) Event: New Britain Region (Sept.12,1965) 08H 40M 12.8S
Station: RKON Distance: 110.4°
(B) Event: Luzon, Phil. Is. (Nov. 24, 1964) 12H 40M 51.4S
Station: RTNM Distance: 112.2°
(C) Event: S. Iran (Dec. 22, 1964) 04H 36M 34.7S
Station: MNNV Distance: 113.7°
(D) Event: Banda Sea (Feb. 14, 1963) 07H 04M 40.8S
Station: HLID Distance: 115.0°
(E) Event: Sandwich Is. (May 25, 1963) 16H 08M 00.8S
Station: DRCO Distance: 116.8°

Figure 2b. Examples of records used to determine $t_{SKKS}-t_{SKS}$.

(F) Event: Sandwich Is. (June 2, 1963) 21H 04M 24.2S
Station: LCNM Distance: 117.5°
(G) Event: New Hebrides Is. (Aug. 14, 1965) 11H 07M 47.1S
Station: DHNY Distance: 121.4°
(H) Event: Tanzania (May 7, 1964) 05H 45M 29.5S
Station: GIMA Distance: 124.4°
(I) Event: New Hebrides Is. (Aug. 14, 1965) 11H 07M 47.1S
Station: HNME Distance: 125.6°
(J) Event: New Britain Region (Sept. 12, 1965) 08H 40M 12.8S
Station: DHNY Distance: 125.6°

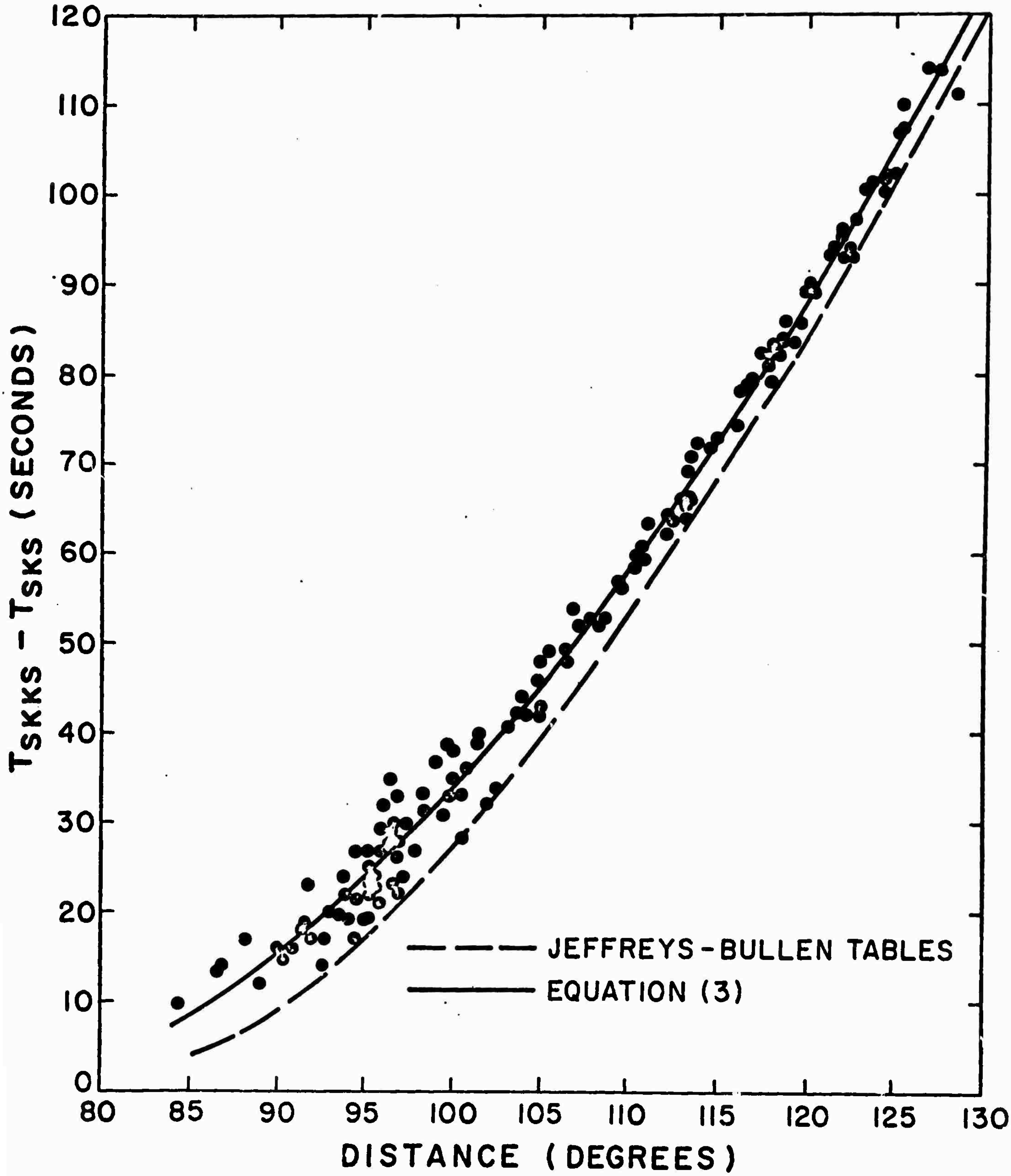
Figure 3. t_K (Δ_K) (solid line) and p_K (Δ_K) as determined from observations of $t_{SKKS}-t_{SKS}$ for $14.47° \leq \Delta_K \leq 41.0°$ and from observations of t_{SKS} for $40.0° \leq \Delta_K \leq 110.0°$. The open circles show the extrapolated values of p_K (Δ_K) and t_K (Δ_K) for values of $\Delta_K < 14.47°$.

Figure 4. The velocity distribution in the outer core as found by Herglotz-Wiechert inversion of p_K (Δ_K). Also plotted for comparison are the distributions of Jeffreys and Randall.

Figure 5. Observations of $t_{SKKKS}-t_{SKKS}$.

(A) Event: Mid-Indian Rise (Dec. 3, 1964) 03H 50M 01.2S
Station: HL2ID Distance: 151.47° (Distance reduced to surface focus 151.55°)
(B) Event: Mid-Indian Rise (Feb. 17, 1966) 11H 48M 00.8S
Station: JPAT Distance: 155.97° (Distance reduced to surface focus 156.02°)
(C) Event: Mid-Indian Rise (Dec. 3, 1964) 03H 50M 01.2S
Station: GEAZ Distance: 161.10° (Distance reduced to surface focus 161.17°)

Figure 6. Δ_{SKKS}, Δ_{SKS}, Δ_{PKP} and Δ_K as functions of bottoming radius. The angles of incidence and refraction at the core-mantle boundary are also shown as functions of bottoming radius so that all quantities can be interrelated.



120
110
100
90
80
70
60
50
40
30
20
10
0
80
85
90
95
100
105
110
115
120
125
130
DISTANCE (DEGREES)
$T_{SKKS} - T_{SKS}$ (SECONDS)
JEFFREYS-BULLEN TABLES
EQUATION (3)

FIGURE 1

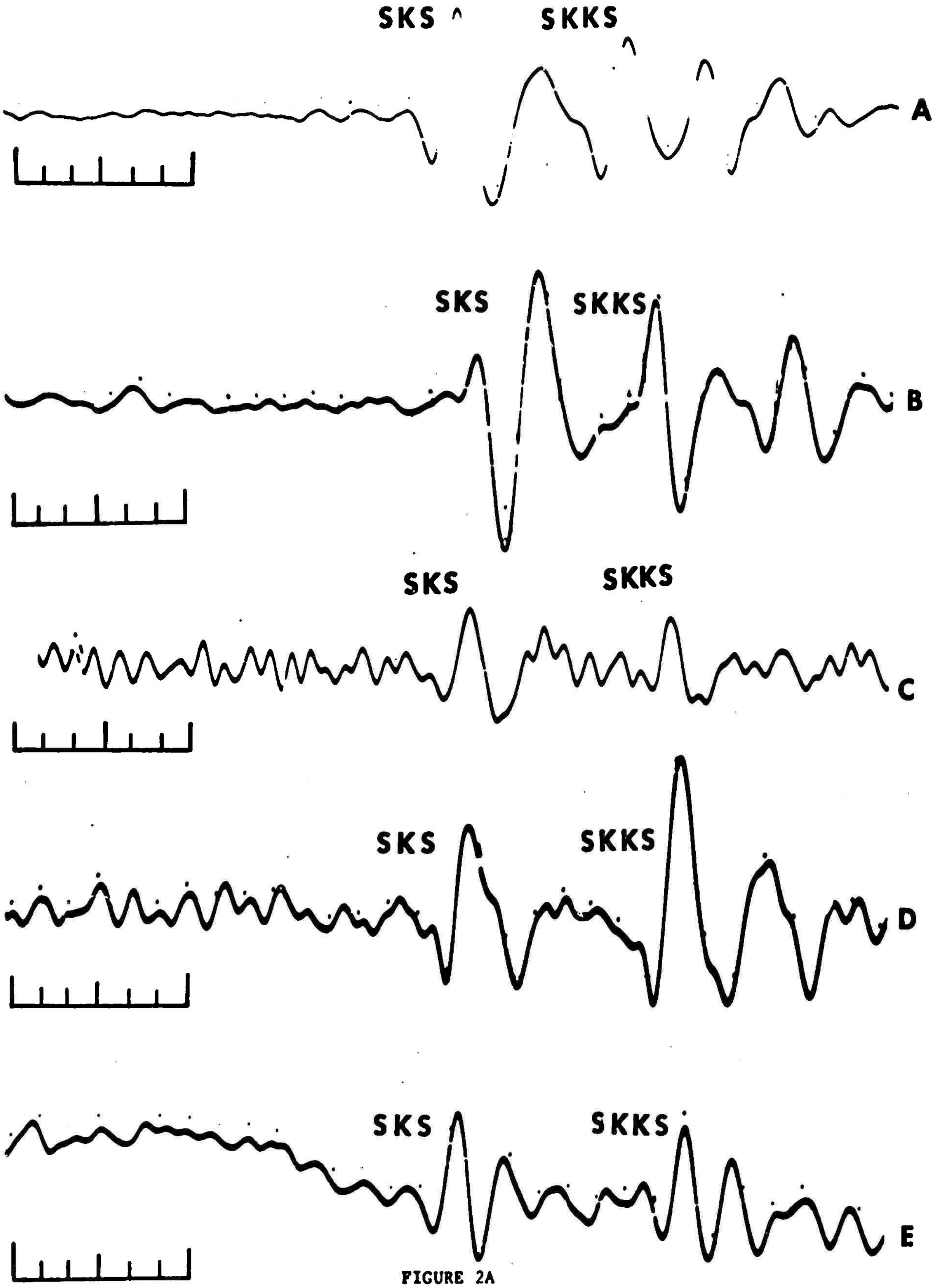


FIGURE 2A

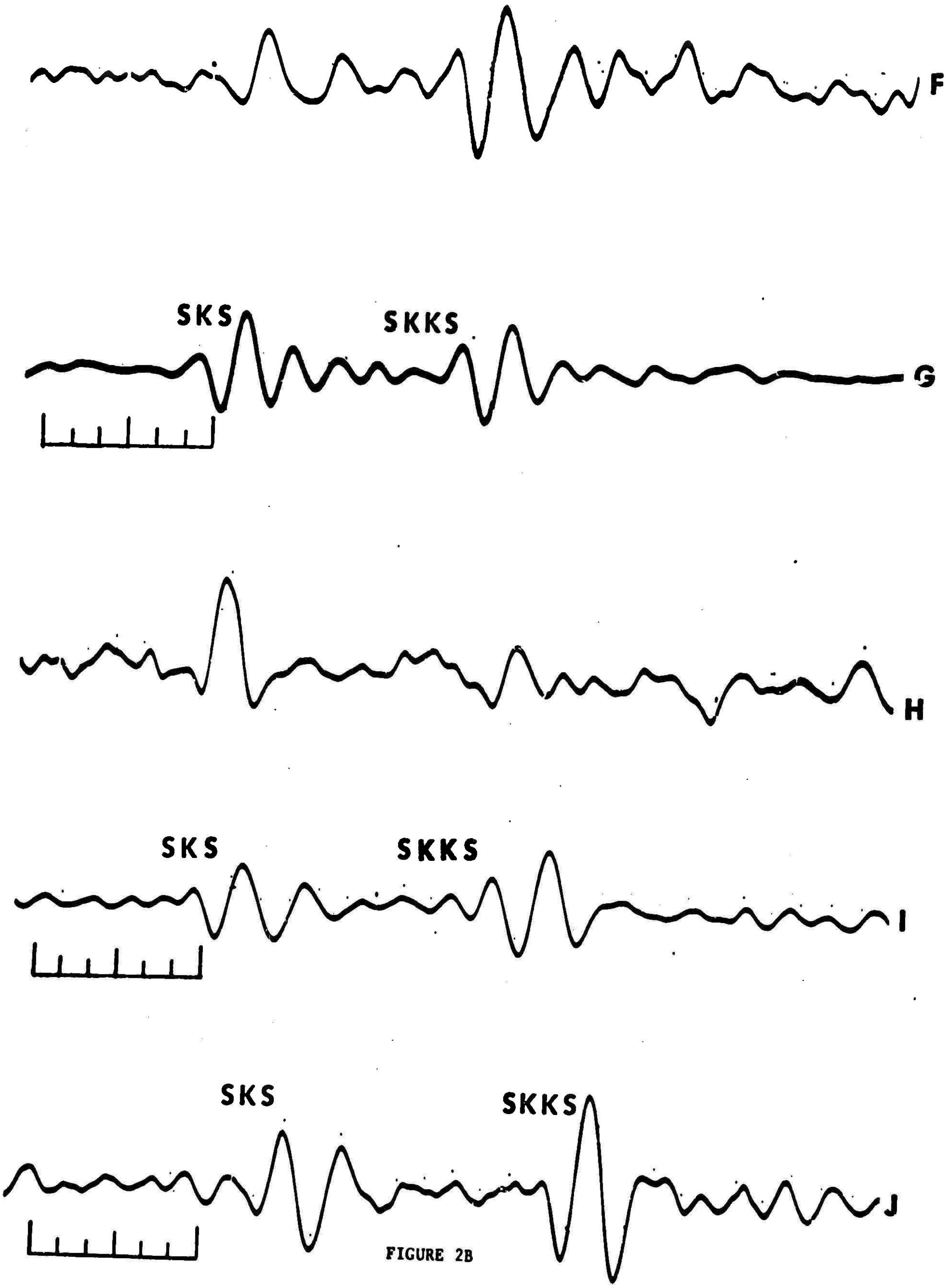
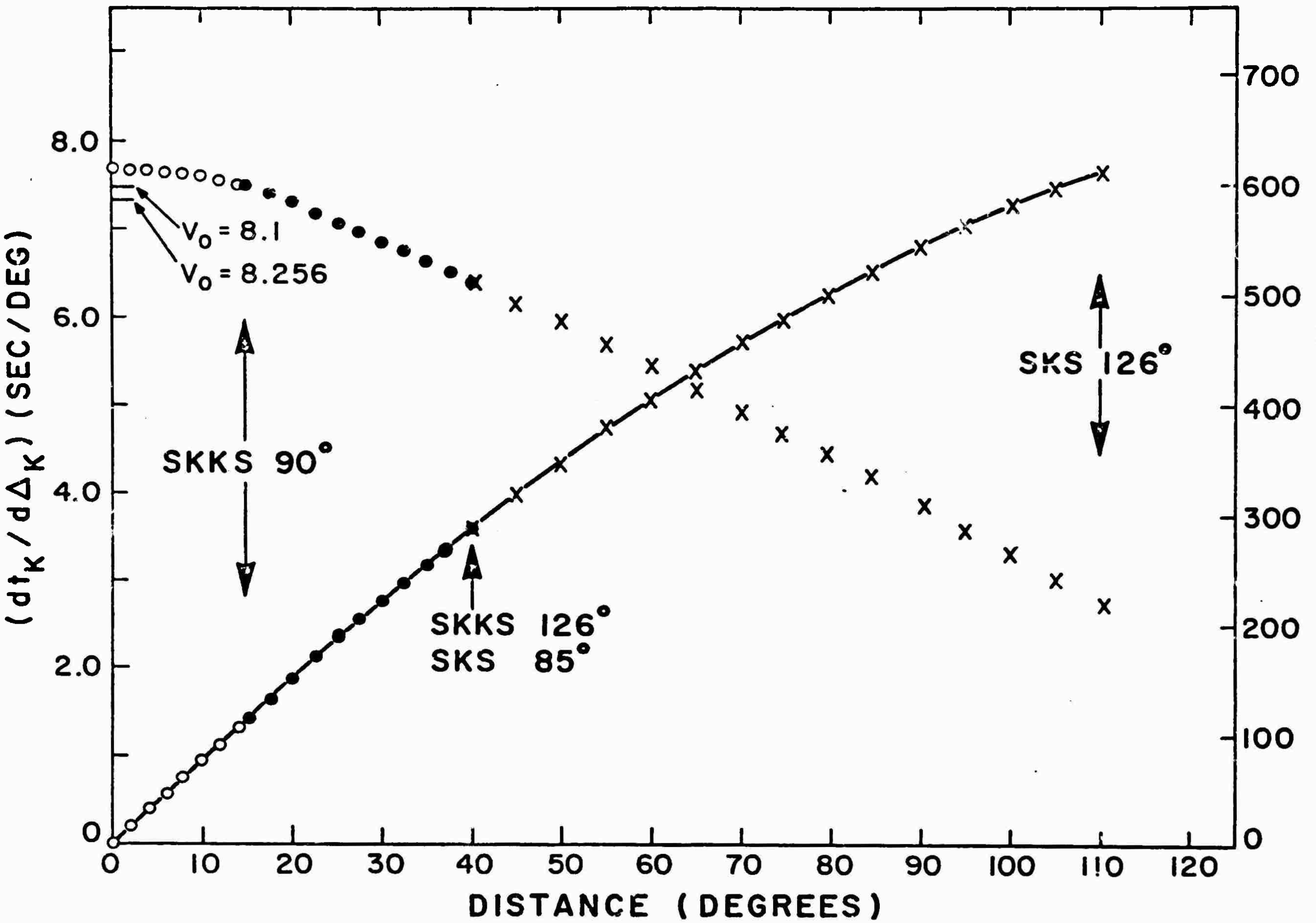


FIGURE 2B

FIGURE 3



$V_0 = 8.1$
$V_0 = 8.256$
SKKS 90°
SKKS 126°
SKS 85°
SKS 126°
$(dt_K / d\Delta_K)$ (SEC/DEG)
t_K (SECONDS)
DISTANCE (DEGREES)
0
2.0
4.0
6.0
8.0
0
10
20
30
40
50
60
70
80
90
100
110
120
0
100
200
300
400
500
600
700

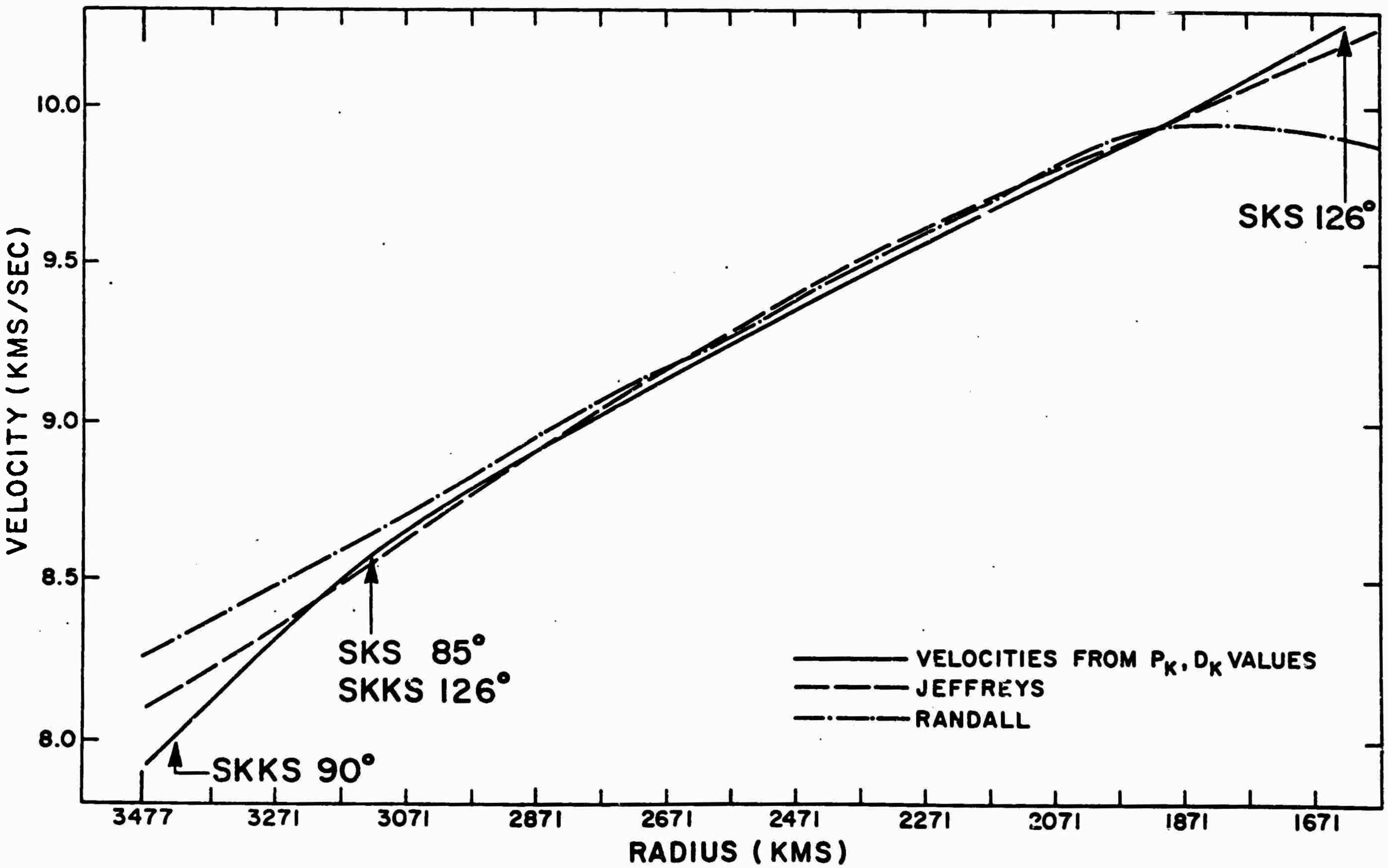

VELOCITY (KMS/SEC)
10.0
9.5
9.0
8.5
8.0
3477
3271
3071
2871
2671
2471
2271
2071
1871
1671
RADIUS (KMS)
SKS 126°
SKS 85°
SKKS 126°
SKKS 90°
VELOCITIES FROM P_K, D_K VALUES
JEFFREYS
RANDALL

FIGURE 4

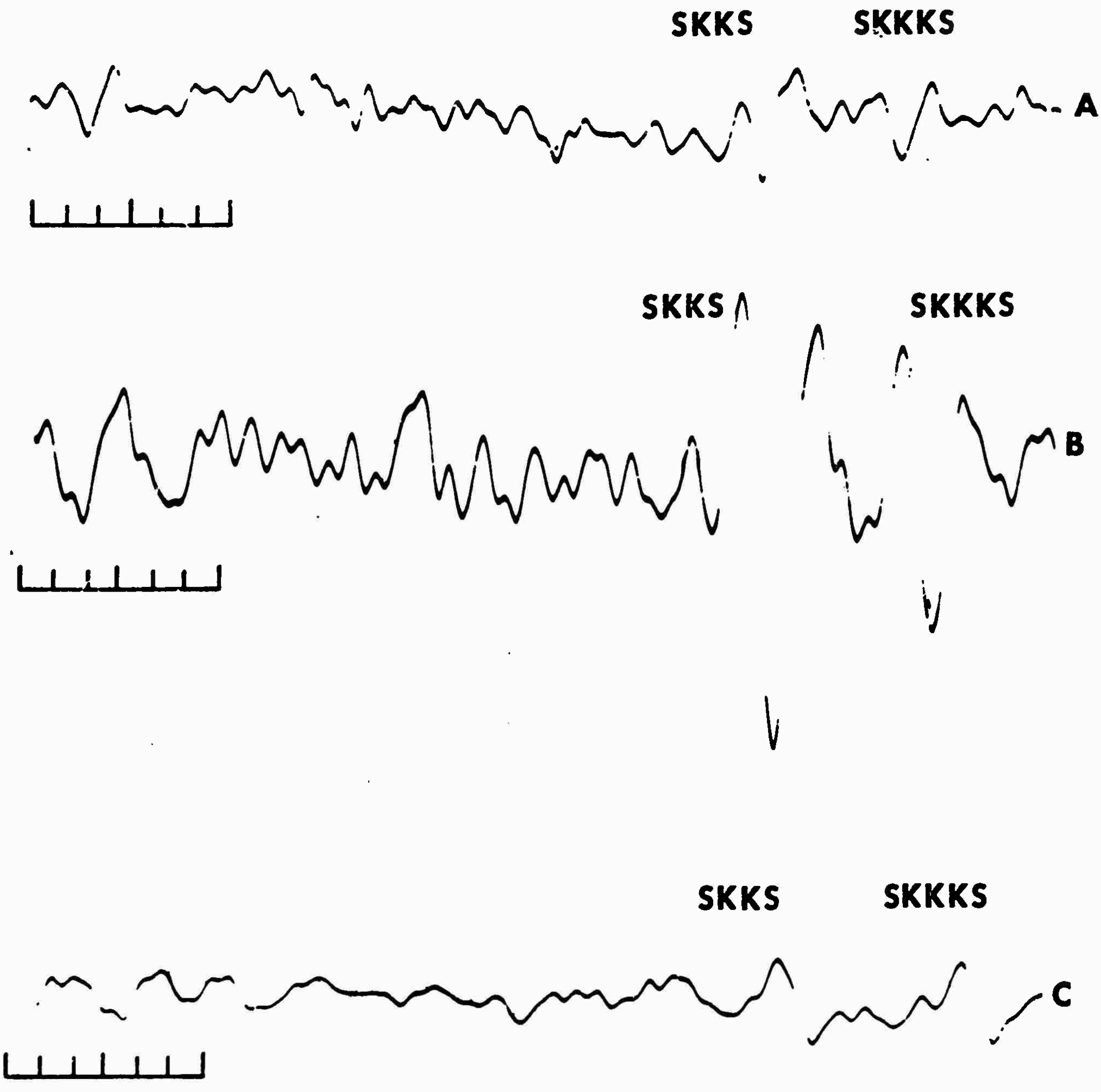
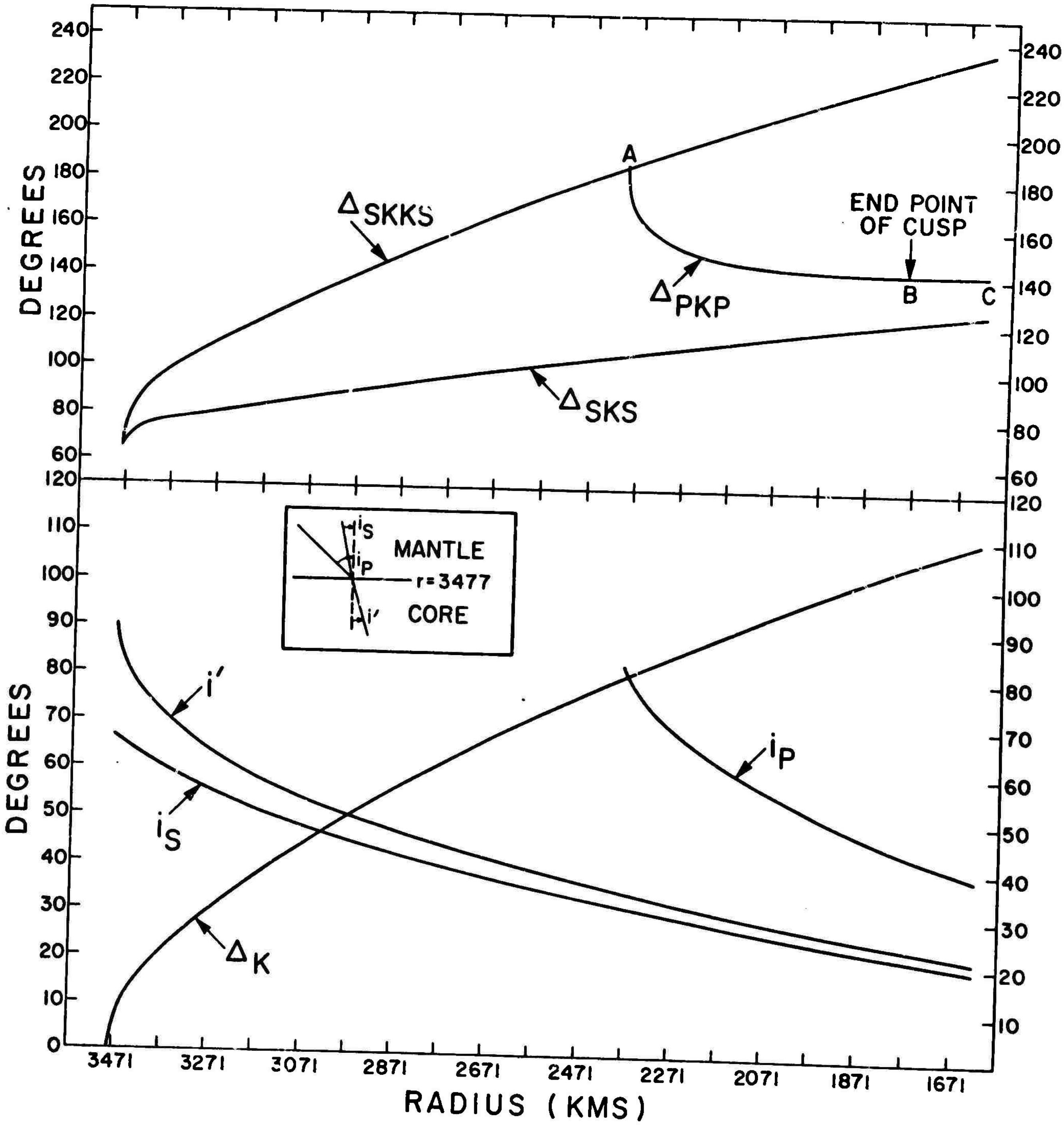


FIGURE 5



DEGREES
Δ SKKS
A
Δ PKP
END POINT OF CUSP
B
C
Δ SKS
i_S
i_P
MANTLE
r=3477
CORE
i′
i′
i_S
i_P
Δ K
RADIUS (KMS)

FIGURE 6

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The University of Texas at Dallas P.O. Box 30365 Dallas, Texas 75230	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

SEISMIC TRAVEL TIME STUDY

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Final 15 Jan 1970 - 14 April 1971 Approved 4 June 1971

5. AUTHOR(S) (First name, middle initial, last name)

Anton L. Hales

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1971	24	8

8a. CONTRACT OR GRANT NO F19628-70-C-0176 b. PROJECT NO 5130 c. DoD Element 62701D d. DoD Subelement n/a	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFCRL-71-0291

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES This research was supported by the Advanced Research Projects Agency.	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (LW) L. G.Hanscom Field Bedford, Massachusetts 01730

13. ABSTRACT

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DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Body wave travel times						
Velocity distribution						
SKKS and SKS arrivals						